STRUCTURAL STRENGTHENING WITH PRESTRESSED CFRP STRIPS WITH GRADIENT ANCHORAGE

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ABSTRACT

This paper presents the principle and the application of an innovative anchorage technique for prestressed carbon-fiber reinforced polymer (CFRP) strips in structural strengthening. Additionally, large-scale static loading tests of retrofitted concrete beams are shown. The gradient anchorage, based on the adhesive's ability to undergo accelerated curing at high temperatures, consists of a purely concrete-adhesive-strip connection without any mechanical devices such as bolts or plates. In a first step, this study summarizes anchorage techniques presented in the literature

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and introduces the basic principles of the new method as well as the necessary components. In a second step, an application on a full-scale RC beam is explained in detail. A commercially available CFRP strip is prestressed up to 0.6 % prestrain and subsequently anchored by sequential epoxy-curing and force-releasing steps at both strip ends. Furthermore, uniaxial tensile tests on the epoxy adhesive and the CFRP strip are used for material characterization and to demonstrate the reinforcing materials' integrity after the heating process. It appeared that prestress losses during the anchoring phase are negligible. Furthermore, the method allows a much faster installation compared to conventional mechanical techniques and increases durability as no permanent steel elements are necessary. The material tests indicate no damage in the reinforcing CFRP strip as well as a sufficiently fast strength development of the adhesive after accelerated curing. Static loading tests on strengthened large-scale RC beams are presented and show the efficiency of a prestressed CFRP strip with gradient anchorage as a retrofitting technique. Finally, first long-term measurements over 13 years on a prestressed strip bonded to a concrete plate revealed small prestrain losses.

Keywords: structural retrofitting, prestressed CFRP strips, epoxy adhesive, accelerated curing, innovative anchorage technique, gradient anchorage

INTRODUCTION

Historically, the use of fiber reinforced polymer (FRP) materials for upgrading existing reinforced concrete (RC) structures started in the early 1980s. Since then, tremendous developments occurred during the following decades, this regarding the materials, their application systems as well as the theoretical knowledge for design purposes. The advantages of composite materials in structural retrofitting applications are well documented in the literature (Bakis et al. 2002). Externally bonded reinforcement (EBR) is the most common flexural strengthening technique with FRP materials. Such reinforcements are glued to the tensile surfaces of the structure to be strengthened. Usually, epoxy adhesives are used as a connector. Among the commercially available FRP, carbon (CFRP) materials are the most spread. Due to their low density, high stiffness, high tensile strength, long fatigue life and less susceptibility to aggressive environments (CEB-Bulletin-No.235 1997), this type of additional reinforcement has gained increasing popularity.

Prestressed FRP for strengthening of RC structures combines the benefits of passive EBR FRP systems with the advantages associated with external prestressing. Over the last two decades prestressed FRPs have been applied and considerable advantages have been pointed out (Svecova and Razaqpur 2000), (El-Hacha et al. 2001), (El-Hacha et al. 2003), (Wight et al. 2001), (Woo et al. 2008), (Pellegrino and Modena 2009), (Motavalli et al. 2011): deflection reduction and acting against dead loads, crack widths reduction, delay in the onset of cracking, strain relief within the internal steel reinforcement, higher fatigue failure resistance, delay in yielding of the internal steel reinforcements, more efficient use of concrete and FRP, reduction of premature debonding failure, increase in ultimate load bearing capacity and increase in shear capacity. Strips, sheets and bars are the most common prestressed FRP shapes, the first ones being the most prominent. Mainly three procedures have been developed to induce prestress in the FRP: cambered prestressing systems (El-Hacha et al. 2001), prestressing against an independent element (El-Hacha et al. 2001), (Xue et al. 2010) and prestressing against the element to be strengthened (El-Hacha et al. 2001), (Woo et al. 2008), (Pellegrino and Modena 2009), (Tateishi et al. 2007), (Neubauer et al. 2007), (França and Costa 2007), (El-Hacha et al. 2009). Among these techniques, the latter procedure can be judged the most suitable for practical application. Like non-prestressed systems, structural epoxy adhesives are generally used to bond the FRP element to the concrete substrate.

At the ends of a prestressed FRP element, special end-anchorage is required in order to transfer the forces from the EBR to the concrete surface and hence to avoid premature peeling-off failure (Triantafillou et al. 1992). Up to now, the proposed end-anchorage systems can be divided in three categories: metallic anchors (Woo et al. 2008), (Pellegrino and Modena 2009), (Xue et al. 2010), (Suter and Jungo 2001), (Xue et al. 2008) non-metallic anchors (Kim et al. 2008), (Berset et al. 2002) and the gradient anchorage (Meier and Stöcklin 2005).

The latter method consists in gradually reducing the prestressing force at the FRP strip ends towards zero over a predefined length. (Wu et al. 2003) use several layers of FRP sheets for the flexural strengthening and for decreasing the level of stresses at the ends. Each FRP longitudinal sheet, at the ends, is anchored by using U-shaped FRP sheets. The other system, proposed by (Meier and Stöcklin 2005) uses a special stressing and heating device. The prestress force gradient is obtained by sector-wise heating and curing of the adhesive followed by step-wise force releasing in the hydraulic jack. With such a system, permanent anchorage (e.g., steel plate) is no longer necessary. Up to now the research performed with this method includes the bond behavior analysis at the anchorage region using lap-shear and prestress-force-release tests (Czaderski et al. 2012) as well as large scale structural tests on retrofitted RC elements. In full-scale tests with prestressed bridge girders with 17 m span (Czaderski and Motavalli 2007), a load increase in ultimate bearing capacity of 45% of the corresponding control structural element and 17.5 % compared to an unstressed CFRP strip reinforcement was noticed. In some cases the CFRP strip even reached its ultimate tensile strength (Meier and Stöcklin 2005), (Kotynia et al. 2011). Long-term bond performance on mechanically anchored prestressed FRP strips was studied for example by Diab et al. (Diab et al. 2009). Additionally, fatigue tests at high temperatures with gradient anchorage were judged satisfying (Kotynia et al. 2011), failure finally always occured by internal steel rupture. In a recently completed research and development project a suitable device for practical application on construction site has been developed for the industry (Michels et al. 2012a). Additionally, a theoretical and experimental investigation was performed in order to study the effect of a prestress force release on the anchorage pulling resistance (Czaderski 2012). This paper presents the method's characteristics, the different necessary components and measurements during a beam retrofitting application. Additionally, tensile tests on both the CFRP strip and the epoxy adhesive after different stress and heating exposure were performed in order to demonstrate the reinforcing materials' integrity after the heating process. Lastly, structural performance is demonstrated by a series of large-scale static loading tests on strengthened RC beams. A first impression on long-term behavior is given by presenting results of several strain measurements in time (13 years) on a prestressed strip used for retrofitting of a concrete plate.

GRADIENT ANCHORAGE

Principle

The gradient anchorage is based on the adhesive's ability to cure faster at high temperatures (Michels et al. 2012b). This accelerated curing property is used to create a non-mechanical anchorage purely composed of the CFRP strip, the concrete surface and the intermediate adhesive layer. The principle is a segment-wise heating and force releasing at the strip end, consequently distributing the total prestress force over several gradient segments and hence avoiding a premature debonding failure. Such a failure might occur in case a too high prestress force would be released in one step (Triantafillou et al. 1992). A schematic representation of the anchorage technique is given in Figure 1. After a first adhesive segment 1 with a length Δl_1 has been cured at high temperature for a defined duration, its strength has sufficiently developed to carry a portion ΔF_1 of the total prestress force F_p, which will subsequently be released. At this stage, the remaining force in the hydraulic jack is F_p-ΔF_1. This procedure is repeated until zero prestress force remains at the strip end. A qualitative force transfer is shown in Figure 2. In case of n accelerated curing/releasing steps, the respective force in the jack at the i^{th} stage is:

$$F_{jack,i} = F_p - \Sigma_{i=1}^{n} \Delta F_i \tag{1}$$

This procedure is evidently followed simultaneously at both strips end. The force in the strip over the free length outside the anchorage area remains theoretically constant at F_p.

Necessary components and installation procedure

A photo of the different components is given in Figure 3. The total device is composed of the following elements: a) base angles, b) clamps, c) aluminum frame, d) manometer, e) hydraulic jack and f) electronic heating device.

The installation procedure is schematically presented in Figure 4. The following steps have to be executed:

- drilling of the temporary anchor bolts a)
- placement of the base angles and the clamps rigidly in the exact position a)
- placement of the CFRP strip (after having spread the epoxy adhesive) a) and closing the clamps with a dynamometric key b)
- fixing of the electronic heating device b)
- fixing of the aluminum frame c)
- installation of the hydraulic jack d)
- loosening of the base plates in order to allow a smooth sliding of the clamp during the prestressing and force releasing

After having installed the different components, the prestressing phase can start. The hydraulic jacks are used simultaneously at both strip ends to deliver the necessary force for the strip elongation. The force should be slowly increased up to the desired prestrain. For the presented laboratory application, which is presented in the following section, two strain gauges were used to electronically follow the rise in strain during the prestress phase. For a construction site application, strain is generally checked by visual control and measuring the length increase on predefined marks on the strip and concrete surface or by applying strain gauges to the CFRP. When the desired prestrain is reached, the valves are closed and the heating of the first segment on both sides starts, lasting for a defined time span. Subsequently, a first force fraction ΔF_1 is released by opening the valves and introduced in the concrete substrate via the cured epoxy adhesive segment. This procedure is repeated until the total prestress force has been completely anchored in the gradient area. The strip is finally cut at both ends, the components can be removed and the temporary anchor bolts can be cut.

Example of beam prestressing

In the present section a strengthening application on a large-scale RC beam (Beam No. 4, see 'Large scale beam tests') with a total length L of 6.5 m and a cross section $b \cdot h$ of 1000 x 220 mm (Figure 5) is presented. Inner steel reinforcement ratio ρ_L was about 0.16 %. 28-days concrete compressive strength on cube $f_{cm,28days}$ was 54.1 MPa. The retrofitting is intended to act against positive bending moments between the supports. The strip cross section was 100 · 1.2 mm ($b_f \cdot t_f$), uniaxial tensile strength $f_{f,u}$ was 2'544 MPa and elastic modulus E_f was 157.8 GPa according to the producer's data sheet (S&P-Clever-Reinforcement-Company-AG 2011). For simplicity reasons, this laboratory retrofitting application was performed from the top with the plate being turned by 180° along its longitudinal axis as shown in Figure 6. With a chosen prestrain $\varepsilon_{f,p}$ of 0.6 %, the force F_p in the laminate corresponds to approximately 120 kN. This stress level of about 1'000 MPa corresponds to 40 % of the ultimate tensile strength $f_{f,u}$. According to previous experimental investigations by the authors (Michels et al. 2012b), a total heating duration t_h of 25 minutes of accelerated curing at approximately 90°C adhesive temperature and a following cooling duration t_{cool} of about 10 minutes represent an optimum for the used epoxy resin in terms of anchorage capacity. Results have shown that bond lengths l_b of 200 and 300 mm with the indicated CFRP strip cross section allow to anchor a maximum force of about 50 and 65 kN, respectively (Michels et al. 2012b). In order to dispose of a sufficient safety when partially releasing the prestress force after accelerated curing, release levels ΔF of 35 and 50 kN were chosen for the mentioned bond lengths. The different releasing steps in relation to the heating device are shown in Figure 7. In total, F_p was released in three steps over a total length of 700 mm, i.e. a first force reduction ΔF_1 of 50 kN over 300 mm (heating elements 1,2 and 3), followed by two consecutive steps ΔF_2 and ΔF_3 of 35 kN over each time 200 mm (heating elements 4,5 and 6,7, respectively). Finally, the epoxy adhesive undergoes accelerated curing over a last segment of 100 mm length (heating element 8) without any remaining prestress force in the jack. This last step is used as a supplementary safety against premature debonding. Additionally to the force (oil pressure) measurement in the hydraulic jack as well as the temperature measurement in the heating elements, temperature in the adhesive layer ($T_{a,1}$ to $T_{a,6}$) in the gradient region was followed by means of thermocouples, whose positions are also indicated in Figure 7. As mentioned earlier, a total cooling duration t_{cool} of 10 minutes was introduced after each accelerated curing step in order to let the adhesive temperature drop under the glass transition temperature (T_g ≈55°C in this case) before proceeding with the force release. In order to further shorten the total application duration, the heating procedure of the subsequent gradient segment is started during the ongoing cooling duration (overlapping of approximately 5 minutes).

In Figure 8, the different characteristic measurements for one anchorage are plotted over time t. In Figure 8 a), prestressing is visible by a rising force in the hydraulic jack. Simultaneously, strain measurements by two gauges (SG1 and SG4, see Figure 14) are presented on a second ordinate axis, eventually presenting a prestrain of about 0.6 % (6000 $\mu m/m$). As soon as the desired force in the jack (and strain in the CFRP strip) is reached, the heating procedure is launched. This is observed by a temperature increase in the heating elements ($T_{h,i}$, Figure 8 b)), almost instantaneously followed by a temperature rise inside the adhesive ($T_{a,j}$, Figure 8 b)). The target values for the temperatures inside the epoxy adhesive $T_{a,k}$ as well as the necessary heating temperature obtained from the heating elements $T_{h,i}$ are explained in detail in (Michels et al. 2012b). In order to increase the temperature in the adhesives as fast as possible, the heating elements had to be configured with an "overheating" temperature. The exact configuration with an initial plateau of 160°C for a time span of 10 minutes followed by an exponential decreasing temperature for 15 minutes derives from an extensive study also documented in the previous reference. After the cooling duration, as it can be seen in Figure 8, the jack force is decreased from 120 to 75 kN (ΔF_1=50 kN over a bond length of 300 mm), while the prestrain over the free length outside the anchorage regions remains constant (Figure 8 a)). Only a minor slip during the first force release resulting in a prestrain loss $\Delta\varepsilon_{f,p}$ of less than 0.01 % is noticed. The total prestress force is afterwards completely reduced to 0 kN by two additional gradient segments of each time 200 mm with 35 kN shear force (ΔF_2 and ΔF_3). At the end, all components will be removed and the temporary anchor bolts are cut. To summarize, a total duration of 130 minutes is necessary to anchor the prestressed CFRP strip. Together with the required preparation work (installation of the bolts, grinding,), a total application duration of about 4 hours can be estimated. Compared to conventional mechanical anchorage systems, which usually require a curing duration at room temperature for the adhesive layer of about 1-2 days, the application of the newly developed device is clearly faster and might be economically more attractive.

In Figure 9, the evolution of the prestrain in the strip for the first 23 days at room temperature is presented. It gets obvious that no decrease in the CFRP strain has occurred, proof of a stable anchorage at the beam end. The slight enhancement after 500 hours is due to the installation of the beam into the test setup for static loading. After the initial installation of the strip on top of the beam, the latter is again moved to its original position (turned by 180°) with the retrofitting strip on the bottom side. Dead load now acts the opposite way than during the anchorage phase and thus increases the strain in the strip.

EXPERIMENTAL INVESTIGATION

Bond characteristics

Recent research at Empa has focused both on the development of a suitable device for practical on-site application as well as on the optimization of the heating and releasing procedure in terms of anchorage length and heating duration (Michels et al. 2012b). A large experimental investigation series of pull-off and prestress/release tests with different laminate thickness (Czaderski et al. 2012), (Michels et al. 2012b) have indicated that after short term curing between 20 and 60 minutes under high temperatures, the epoxy adhesive has gained sufficient (tensile and shear) strength carrying loading forces high enough to provoke debonding failure in the concrete substrate. Compared to specimens cured for 2 to 3 days under room temperature, accelerated curing at high temperatures (approximately 90°C adhesive temperature) evoked higher anchorage resistances, indicating more distributed shear stresses over the bond lengths. This behavior might be due to a lower elastic modulus after the short-term curing process compared to a stiffer material behavior after a longer curing period at room temperature. The cited references demonstrate that a lower elastic modulus of the epoxy involves a higher active bond length and thus higher anchorage resistances, due to the low tensile resistance of concrete. In this paper, the stated characteristics about the epoxy adhesive's elastic modulus are experimentally verified and presented in the upcoming sections. A possible temperature influence on the tensile characteristics of the CFRP strip is investigated, too.

Tensile tests

This section presents experimental analysis on both the epoxy adhesive and the CFRP strip. The first part describes uni-directional tensile tests performed on epoxy resin specimens cured at room temperature for 3 days and cured at high temperature during a short time span, respectively. In the second part, CFRP strip specimens after different heating and stressing treatment were submitted to uniaxial tension in order to assess a possible strength reduction during the anchorage procedure. The goal of the investigation is the assessment of the materials' mechanical performance (stiffness and tensile strength) during the gradient application conditions.

The tensile properties of the CFRP strip with a thickness t_f of 1.2 mm were evaluated according to the ISO 527-5:1997(E) (ISO-527-5) standard. The following configurations were analyzed: unstressed (CFRP-REF), prestressed (CFRP-PRE) and prestressed/heated (CFRP-PH). Prestressed means applying a strain of 0.6 %, identical to the prestress level used for the gradient anchorage. The heating procedure also follows exactly the configuration from the gradient method presented earlier in Figure 8. Temperature $T_{h,i}$ for the heating elements evolves from an initial value of 160°C for 10 minutes followed by an exponential decrease to 120°C during 15 minutes. In addition to the investigation of the mechanical properties, physical properties of the distinct series were assessed by visual inspectional and by SEM (Scanning Electron Microscope). Each series was composed of 6 specimens for which the geometry is included in Figure 10. A servo-controlled testing machine was used to perform the tests under a displacement rate of 2 mm/min and a clip gauge with a measuring length of 50 mm was mounted at the middle of each specimen for evaluating the tensile strain. The applied force was recorded by a load cell with a maximum capacity of 200 kN. Prior to the tensile tests, the geometry of all the specimens was assessed by using a digital caliper at 3 specific locations, namely at the specimen middle and at 25 mm distance on both sides (top and bottom). Eventually, elastic modulus and tensile strength evaluation was performed by defining a theoretical cross-section with the average width and thickness dimensions resulting from the three performed measurements. Visual inspection did not reveal any difference between the stressed and heated specimens compared to the reference strips. SEM observations of the strips' cross sections for the series CFRP-REF, CFRP-PRE and CFRP-PH (one for each series) are shown in Figure 11 a), b) and c), respectively.

No clear differences were found in these scanning electron microscope observations. Apparently the density of carbon fibers is slightly higher for the CFRP-PRE and CFRP-PH specimens than for the reference strip. This marginal variation was found to be about 8 % and 6 %, respectively, a finding that can be justified with the eventual straightening caused by the prestressing. The tensile test results are summarized in Table 1. Negligible variation on the physical and mechanical properties was observed, allowing to say that the adopted procedure for the gradient anchorage application does not affect the overall mechanical behavior of the CFRP strip.

For the epoxy adhesive, two configurations are analyzed. For the first category, the formwork with the mixture is kept under constant room temperature (22°C) in a climate chamber for 3 days prior to testing. The second category is subjected to accelerated curing at approximately 90°C (adhesive temperature T_a, see Figure 8) for 25 minutes, followed by a cooling duration of about 10 minutes before the tensile test. The configuration for temperature evolution $T_{h,i}$ of the heating elements was also kept identical to the one used for the beam application presented in Figure 8. Heating is applied by means of the same heating box (Figure 3 and 4) that has also been used for the anchorage application. In this case, the heating device was put on top of the formwork in which the adhesive mixture has been previously introduced. In order to simulate the exact situation as during the prestressing procedure, a piece of CFRP strip was introduced between formwork and heating device, a film was additionally placed between strip and adhesive in order to avoid chemical adhesion. The epoxy resin is a thixotropic, grey two-component mixture, which is commercialized by S&P Clever Reinforcement Company under the trademark S&P Resin 220 epoxy adhesive (S&P-Clever-Reinforcement-Company-AG 2012) with the characteristics summarized in Table 2. ISO 527-2:2012(E) standard (ISO-527-2) was followed in order to evaluate the tensile properties. A servo-controlled testing machine was used to perform the tests under a displacement rate of 1 mm/min. A clip gauge of 50 mm of length was mounted at the middle of each specimen for evaluating the modulus of elasticity (Figure 12). The applied force was measured by means of a load cell with 20 kN of maximum capacity.

Prior to the tensile tests, the geometry of all the specimens was assessed using a digital caliper. Three measurements were done along the gauge length, namely, the thickness t and width b, at the top, middle and bottom part of the specimen (bottom and top part being distanced from the middle part by 25 mm). The three values were grouped into an average thickness and width in order to assess an elastic modulus E_f. According to the ISO 527-2 (ISO-527-2), the elastic modulus shall be determined between strain values of ε_1=0.00005 and ε_2=0.00025. Since not all the specimens reached the level of strain of 0.00025, a second approach was adopted in order to compare the performance of all the series. A maximum strain ε_2=0.0015 was used. This level was selected as the minimum value reached by all the specimens considered in the present analysis. Figure 13 shows stress-strain curves and Table 3 summarizes the results for both the tensile strength and the elastic modulus for the two different curing conditions. It gets obvious that the elastic modulus is clearly lower after a short-term curing process at high temperature compared to the reference specimens cured at room temperature for 3 days. This confirms the assumptions presented in 'Bond characteristics', stating that a lower elastic modulus exists for the 25 minutes heating at 90°C. Tensile strength after short-term curing is lower, too. However, with the heating configuration as presented in Figure 8, this characteristic is in the present case not of high importance as the concrete substrate represents the weakest link in the system (Czaderski et al. 2012), (Michels et al. 2012b).

Large scale beam tests

This section summarizes the static loading tests of four strengthened RC beams with gradient anchorage, among them Beam No. 4 presented under 'Example of Beam Prestressing'. The main objective of this section is the demonstration of the gradient anchorage's efficiency. The test setup is shown in Figure 14. The beam was simply supported with a total span of 6 m and subjected to 6-point loading. Average concrete compressive strength on cube at 28 days as well as on the testing day (strength value for Beam 4 was estimated according to (fib bulletin1) as no test result was available) and exact prestrain levels $\varepsilon_{f,p}$ in the CFRP strip for strengthening are listed in Table 4. Equal point loads were applied every 1.2 m under controlled displacement (3 mm/min) at midspan. Deflection at midspan was measured by two displacement transducers, the forces recorded with load cells. Two strain gauges (SG1 and SG4) were mounted on the CFRP strip prior to strengthening in order to assess tensile strain during the prestressing procedure (see 'Example of beam prestressing'). Additional four strain gauges (SG2, SG3, SG5 and SG6) were installed after strengthening. Location of the measurement points is also given in Figure 14.

The total force-midspan deflection ($4{\cdot}F, w$) diagram of the loading test for all the beams is given in Figure 15. Due to a technical issue no forces were saved for Beam 1 during the loading process. Final bearing load of this member was approximately

$4{\cdot}F_u$=80 kN. For comparison purposes, a strengthened beam is calculated by means of a simple cross section analysis (CSA) under the assumption of tensile failure of the CFRP strip at 1.6 % tensile strain (S&P-Clever-Reinforcement-Company-AG 2011). Furthermore, the calculated curve of a reference beam with the same cross section but without any additional external reinforcement is displayed. A first beneficial effect is the clear enhancement of the total cracking load $4{\cdot}F_{cr}$. For the four beams, the ultimate load occurs cleary after steel yielding. The total bearing load ($4{\cdot}F_u$), deflection at failure and maximum CFRP tensile strain at failure are summarized in Table 4. It is visible that for all specimens the failure load is reached before the CFRP strip is able to develop its full tensile strength. Tensile strain increase $\Delta\varepsilon_f$ in the CFRP strip up to failure in the range of 0.57 to 0.83 % can be noticed. For Beams 1 and 3 ultimate failure strain was almost attained. Maximum forces $4{\cdot}F_u$ are in the current case strongly increased from 16.6 kN for the reference case to values above 65 kN (>290 %).

Long-term behavior

(Stöcklin and Meier 2001) presented strain measurements along the length of a 2.4 m long prestressed CFRP strip with gradient anchorage applied in the year 2000 on a concrete slab. In the middle part of the strip over approximately a length of 0.8 m the strain is more or less constant. A mean prestrain of 0.55% was measured in this area. The slab was stored in the laboratory since then. Figure 16 shows actual photos of the test sample with the prestressed CFRP strip and results of long-term measurements. It can be seen that after almost 13 years the mean prestrain reduced only slightly from 0.55 to 0.51%, most likely due to creep of concrete.

CONCLUSIONS

The presented R&D activities allow to draw a certain number of conclusions. In the framework of an industry-based project, an efficient heating device has been developed to complete the existing prestressing system. First advantage of the new tool is its easy handling on site. Each component of the total system can be carried by one single person, hence reducing person costs by avoiding a large number of necessary participants. Due to the absence of remaining metallic components such as bolts or plates, the anchorage has a more appealing appearance under service and durability is improved, too. A further positive aspect is the short application time. Including all preparation as well as dismantling steps, the total necessary time span is about 4 hours. Compared to conventional mechanical solutions available on the market, generally requiring 1-2 days of epoxy curing at room temperature before the anchorage is ready for use, the new system is clearly faster. All the above mentioned positive points make the system attractive for future applications. Material testing have shown that the CFRP strip remains undamaged during the heating process, post-heating tensile strength is identical to the reference values. Shortly after the accelerated curing, the epoxy adhesive is softer than the room temperature cured equivalence. However, the temporarily reduced elastic modulus is of advantage for the current application, as earlier research by the authors has prooven. Due to the lower stiffness, an attenuation of the shear stresses in the gradient region is registered. The lower tensile strength after short-term heating is of no importance, as the curing of the adhesive has sufficiently advanced for carrying shear stress. Short-term static loading on four retrofitted large-scale beams have shown the efficiency of such a prestressed CFRP strip as additional reinforcement. Both cracking and ultimate loads were significantly increased. A first long-term analysis of the gradient anchorage behavior in time has shown satisfying results with only minimal strain losses.

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TABLE 1: Average results of the unidirectional tensile tests on CFRP strip specimens after different stress and heating conditions (CFRP-REF: unstressed, CFRP-PRE: prestressed, CFRP-PH: prestressed and heated)

Specimen		b_f [mm]	t_f [mm]	F_{max} [kN]	$f_{f,u}$ [MPa]	E_f [GPa]
CFRP-REF	X_{min}	15.1	1.2	44.8	2548.7	157.6
	X_m	15.1	1.2	49.1	2761.2	162.0
	X_{max}	15.1	1.2	54.0	3007.5	167.8
	CoV	0.1%	0.7%	7.6%	6.9%	3.2%
CFRP-PRE	X_{min}	15.1	1.2	45.3	2572.3	158.9
	X_m	15.1	1.2	48.2	2707.6	163.6
	X_{max}	15.1	1.2	51.2	2901.0	169.4
	CoV	0.1%	0.7%	5.2%	5.4%	2.5%
CFRP-PH	X_{min}	15.1	1.2	44.9	2427.3	150.4
	X_m	15.2	1.2	48.0	2632.2	161.2
	X_{max}	15.2	1.2	51.5	2889.5	166.6
	CoV	0.3%	1.4%	4.7%	6.0%	3.5%

TABLE 2: Physical and mechanical characteristics of the S&P Resin 220 epoxy resin according to the producer's data sheet S&P Clever Reinforcement

Property	*Value*
Components	A (resin) and B (hardener)
Color	Light grey Component A
	Black Component B
	Light grey Final mix (A+B)
Mixing ratio	4 : 1 (A : B) by weight or volume
Glass transition temperature	$\geq$ 56°C
Pot life	$\geq$ 60 min. at +20°C
Bending tensile strength	$\geq$30 MPa
Compression strength	$\geq$90 MPa
Adhesive strength	$\geq$3 MPa (on concrete and on S&P laminates)

TABLE 3: Elastic modulus E_a and tensile strength $f_{a,u}$ of the epoxy specimens cured at high temperature (HT, 90°C) for 25 minutes and cured at room temperature (RT, 22°C) for 3 days

Specimen	*HT curing* E_a [GPa]	*RT curing* E_a [GPa]	*HT curing* $f_{a,u}$ [MPa]	*RT curing* $f_{a,u}$ [MPa]
1	5.9	6.9	11.8	21.9
2	5.7	(*)	16.1	(**)
3	5.2	7.9	12.5	20.6
4	4.3	7.9	13.2	21.5
5	4.0	7.9	9.5	19.0
6	3.7	7.8	8.8	19.9
X_{min}	3.7	6.9	8.8	19.0
X_m	4.8	7.7	12.0	20.6
X_{max}	5.9	7.9	16.1	21.9
CoV	15.6%	5.4%	16.5%	5.5%

TABLE 4: Summary of static beam tests (*estimated according to fib-bulletin 1)

Beam	$f_{cm,cube,28}$	$f_{c,cube,testing}$	$\varepsilon_{f,p}$	$4 \cdot F_{tot}$	w_u	$\varepsilon_{f,u}$	$\Delta\varepsilon_f$
-	[MPa]	[MPa]	[%]	[kN]	[mm]	[%]	[%]
1	56.8	63.2	0.59	$\sim$80	127.4	1.42	0.83
2	54.3	57.7	0.59	69.9	91.2	1.16	0.57
3	52.2	54.0	0.60	80.9	125.3	1.38	0.78
4	54.1	69.4*	0.61	70.5	98.8	1.28	0.67

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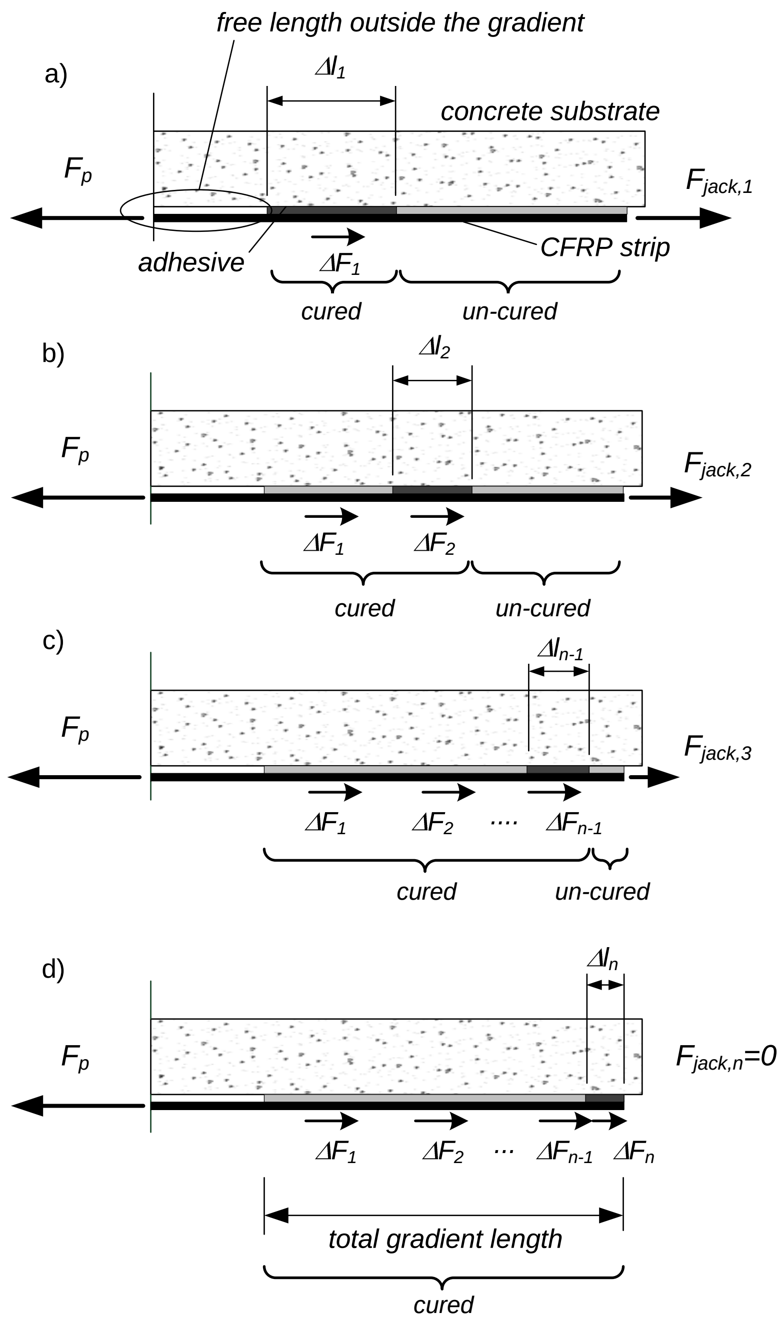


FIG. 1: Schematic representation of the gradient anchorage

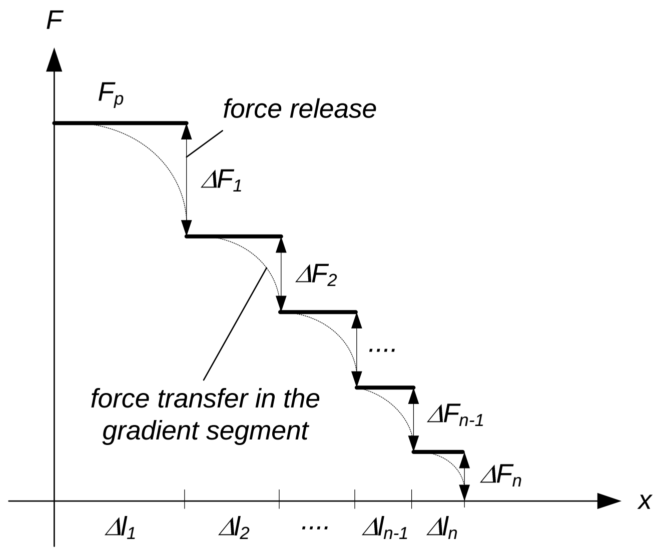


FIG. 2: Force transfer in the different gradient segments

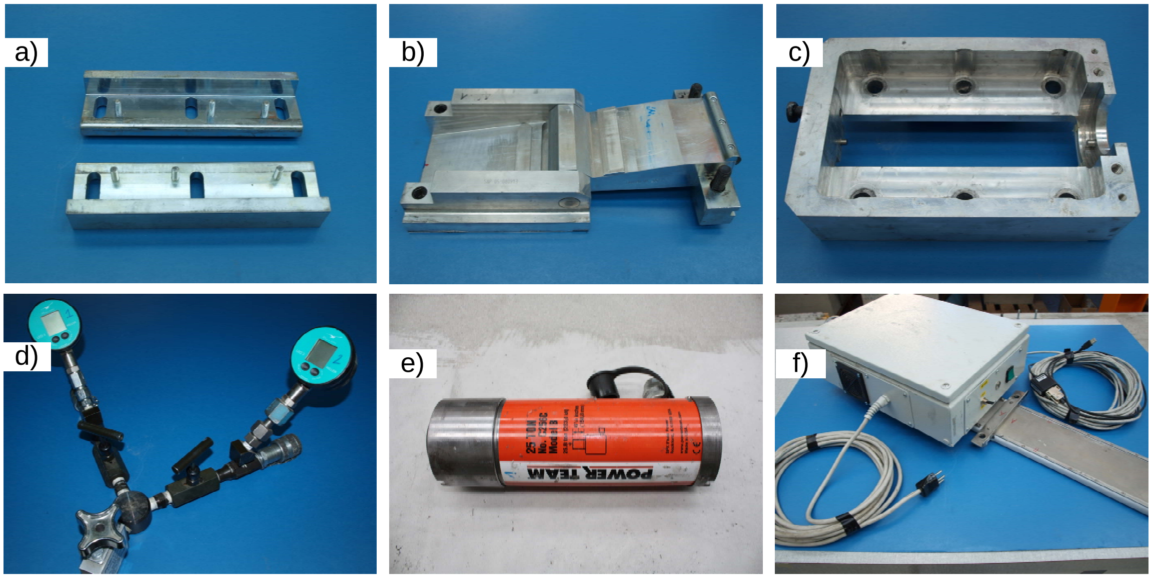


FIG. 3: Different components of the anchorage device: a) base angles, b) clamps, c) aluminum frame, d) manometer and valves, e) hydraulic jack and f) electronic heating device

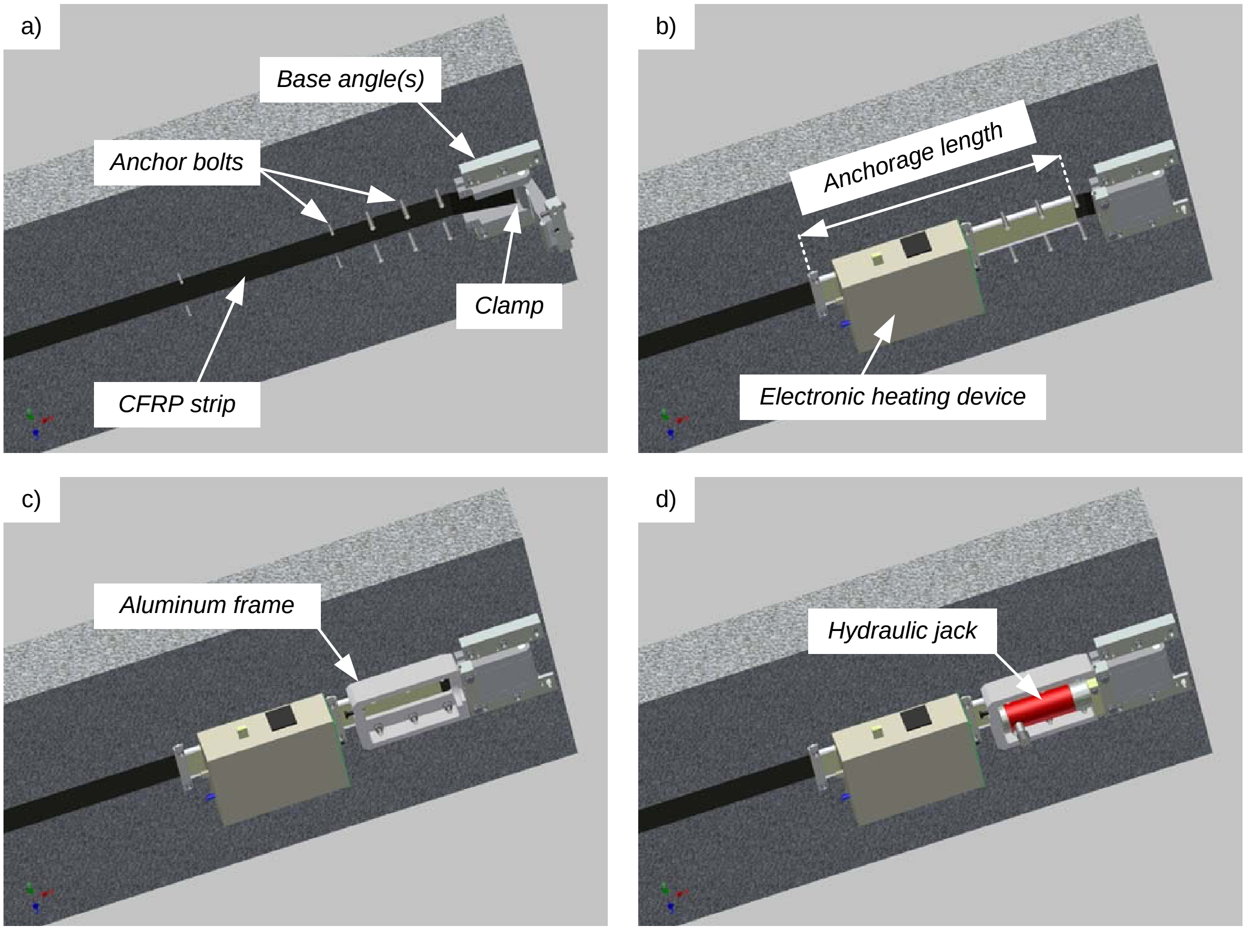


FIG. 4: Installation procedure for the gradient anchorage devices

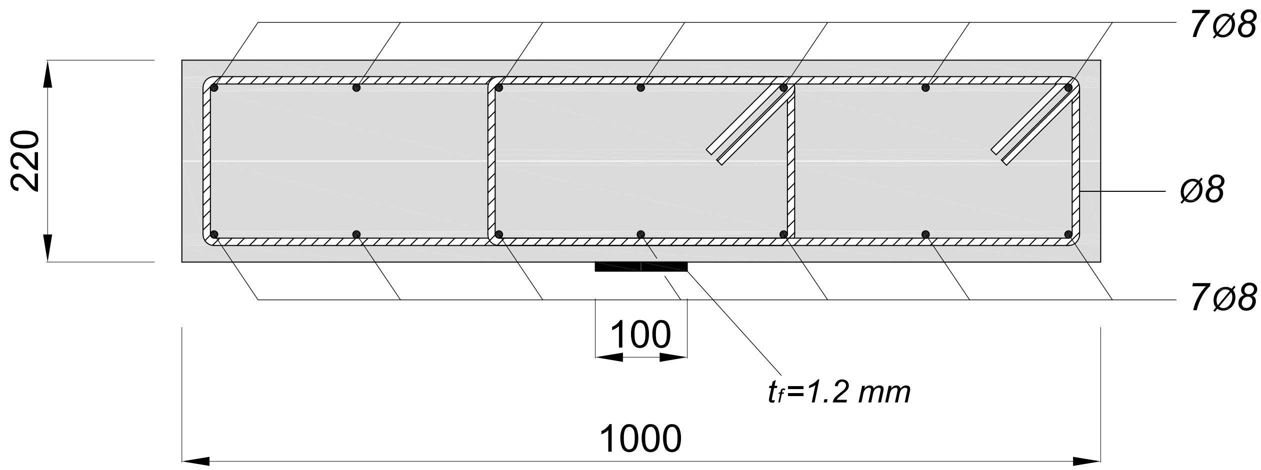


FIG. 5: Cross section of the strengthened RC beam (dimensions in [mm])

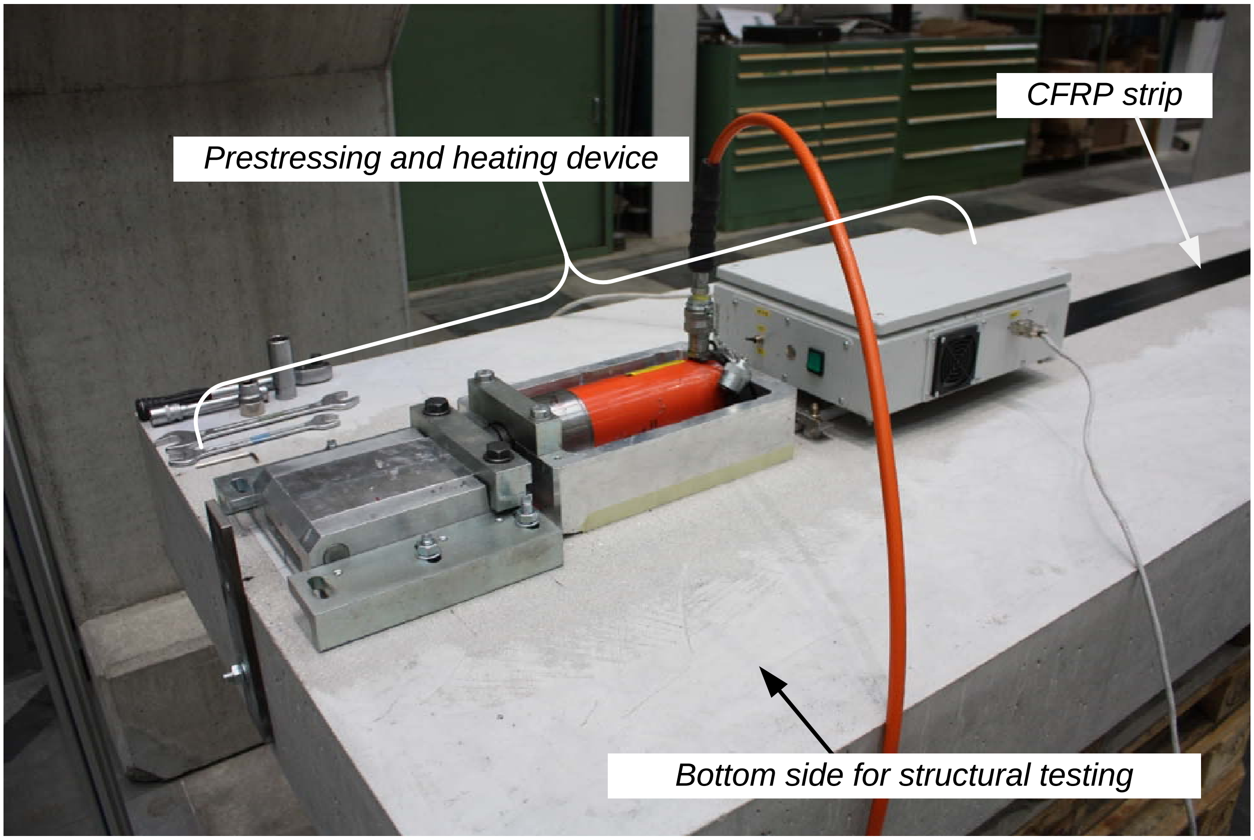


FIG. 6: Plate bottom side during the strengthening application

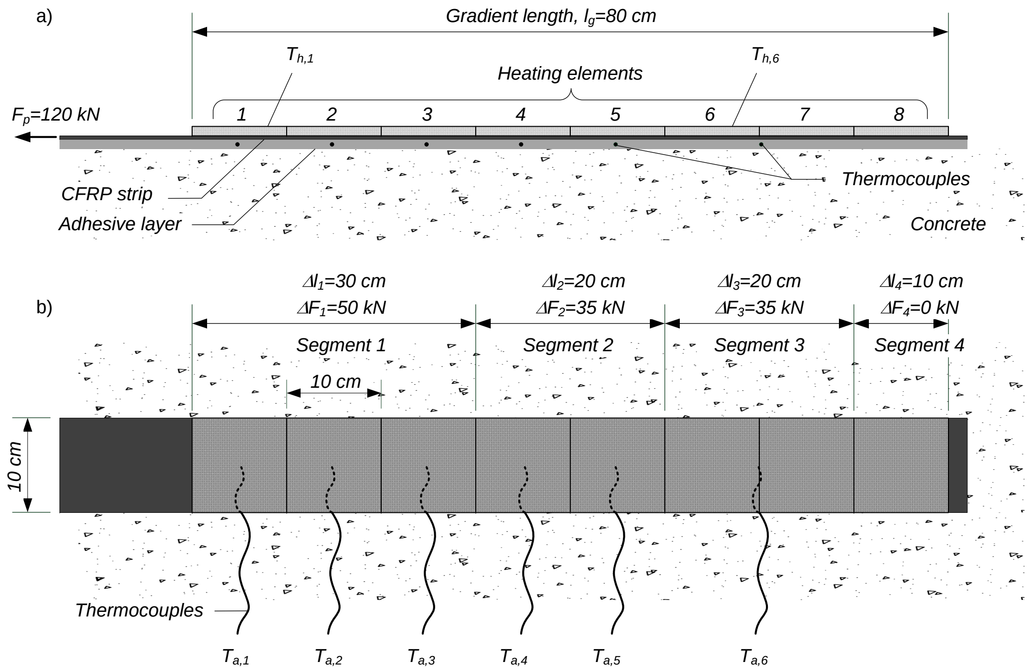
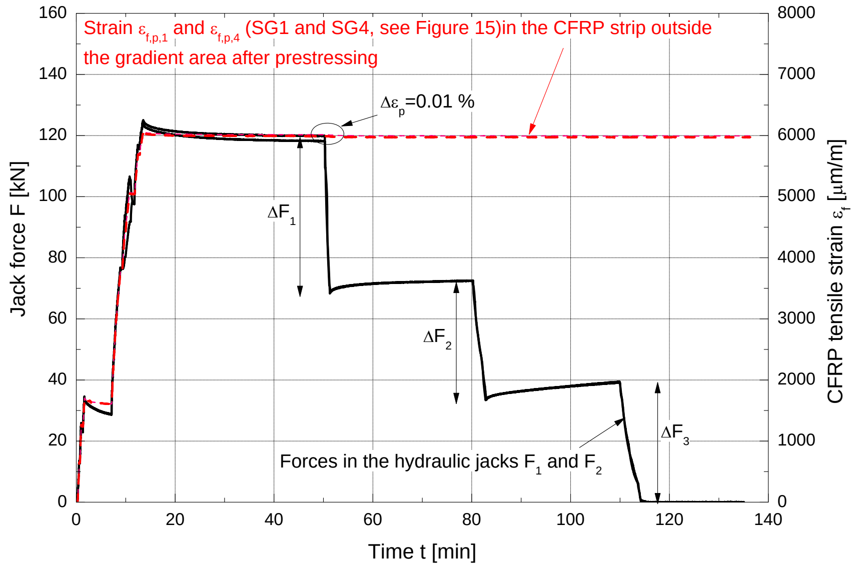
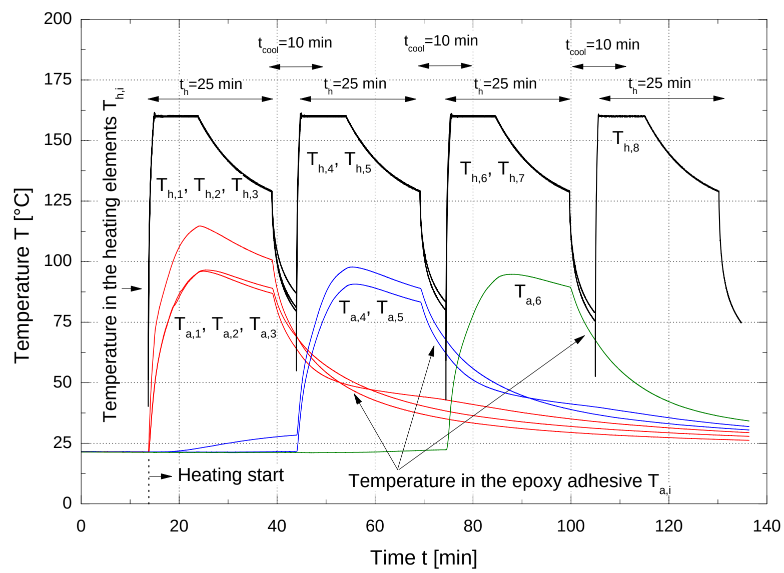


FIG. 7: Heating and force release configuration for the strengthening application, a) Side view, b) Top view



(a)



(b)

FIG. 8: a) Jack force F and CFRP strain $\varepsilon_{f,p}$ (outside the gradient area) evolution over time t, and b) Temperature evolution over time t in the heating elements $T_{h,j}$ and in the adhesive $T_{a,k}$

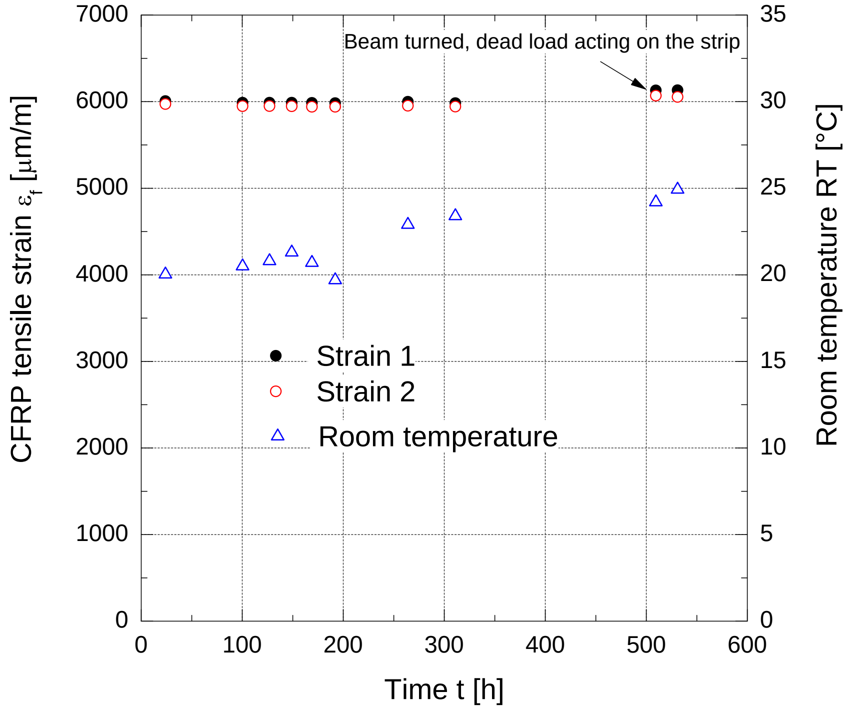


FIG. 9: CFRP tensile strain ε_f evolution over time after anchoring

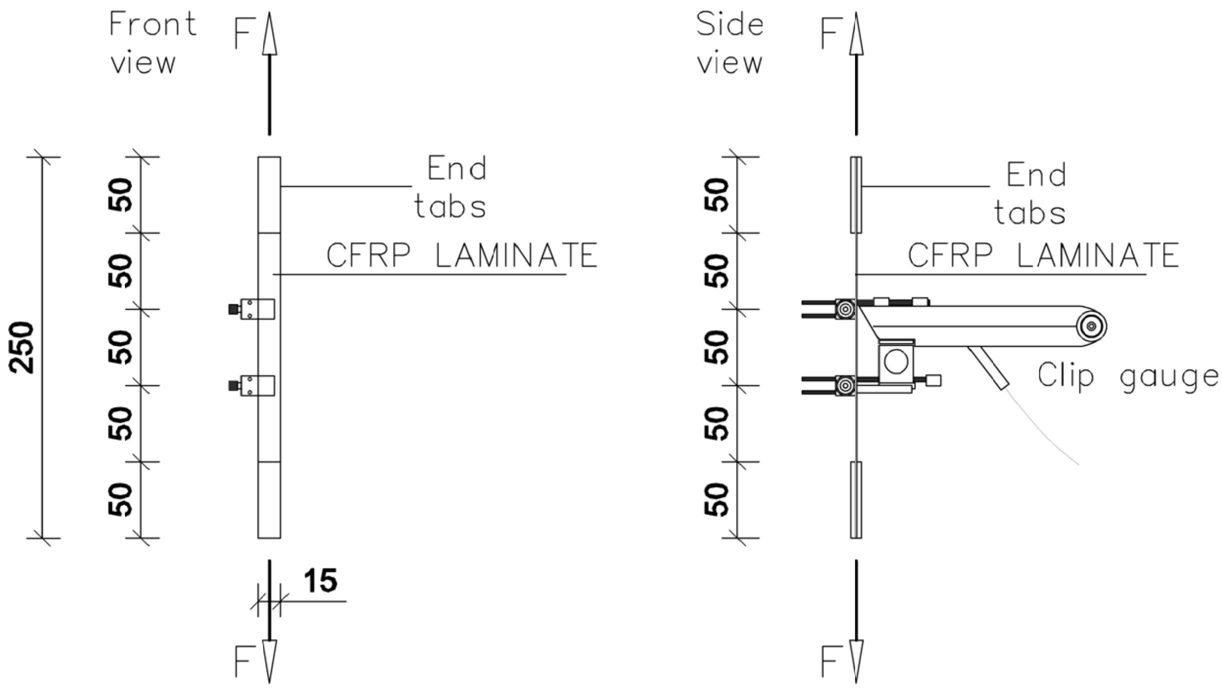


FIG. 10: Specimen dimensions (in [mm]) and test configuration for the CFRP tensile tests

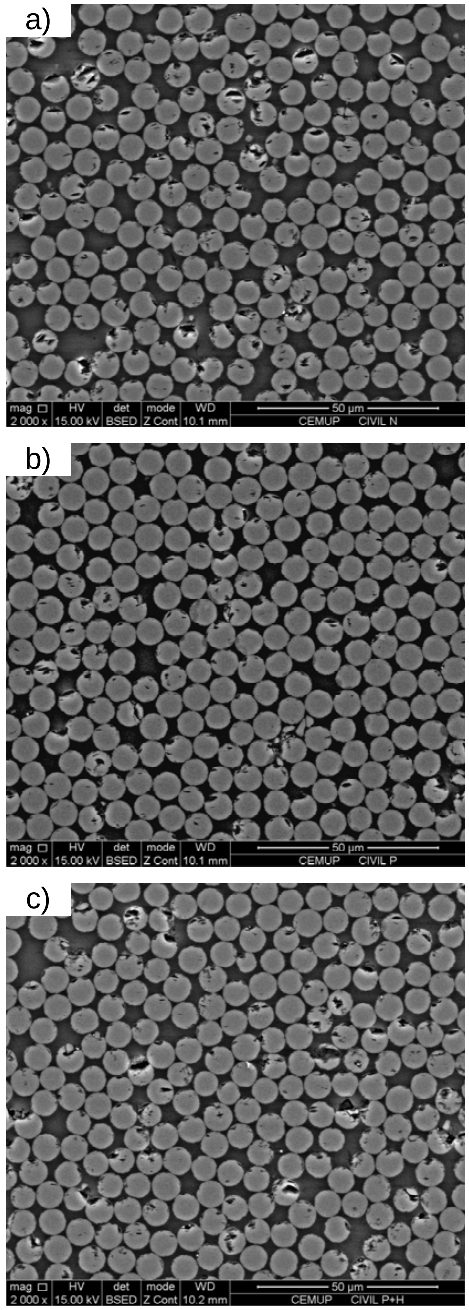


FIG. 11: SEM images of CFRP samples: a) REF - reference, b) PRE - prestressed (σ_p=1'000 MPa) and c) PH - prestressed (σ_p =1'000 MPa) and heated ($T_a \approx$90°C)

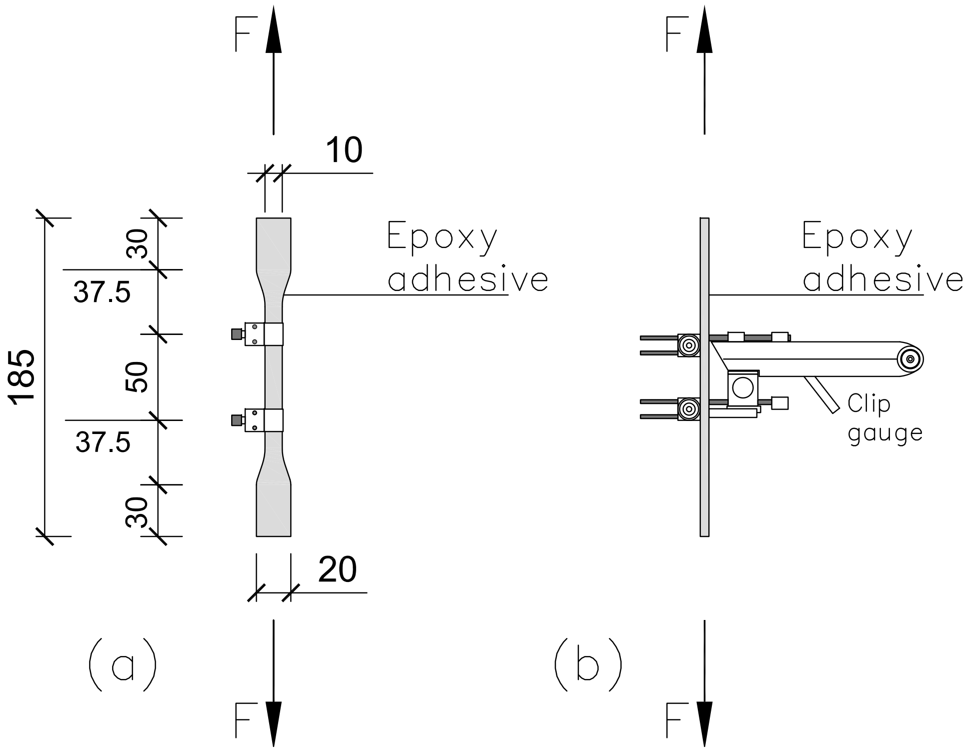


FIG. 12: Specimen dimensions (in [mm]) and test configuration for the epoxy resin tensile tests

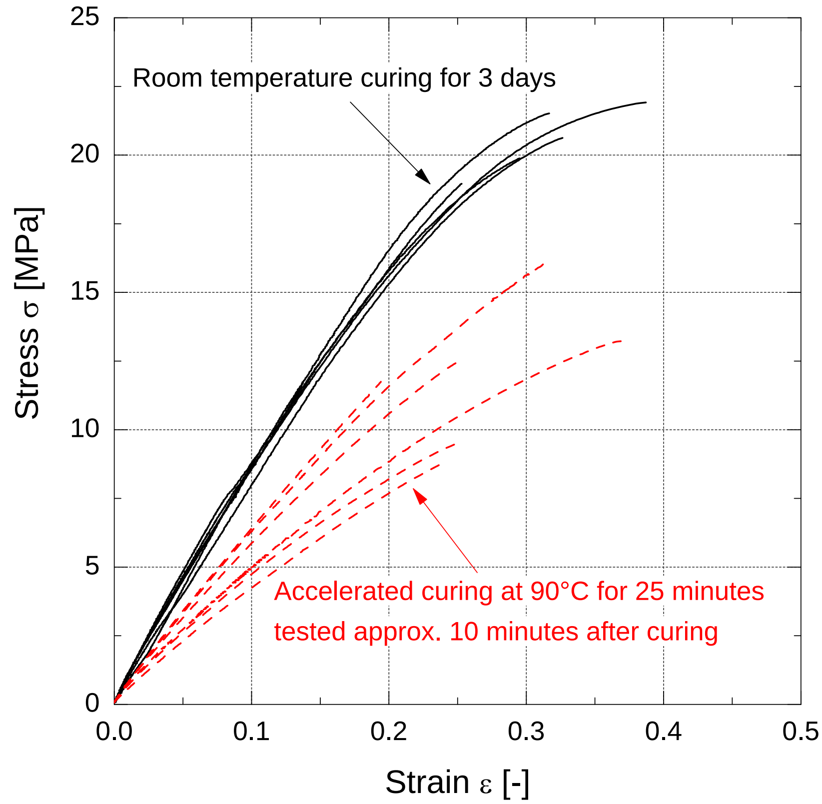


FIG. 13: Stess-strain curves from the uniaxial tensile tests on epoxy specimens - RT cured for 3 days and accelerated curing for 25 minutes at 90°C

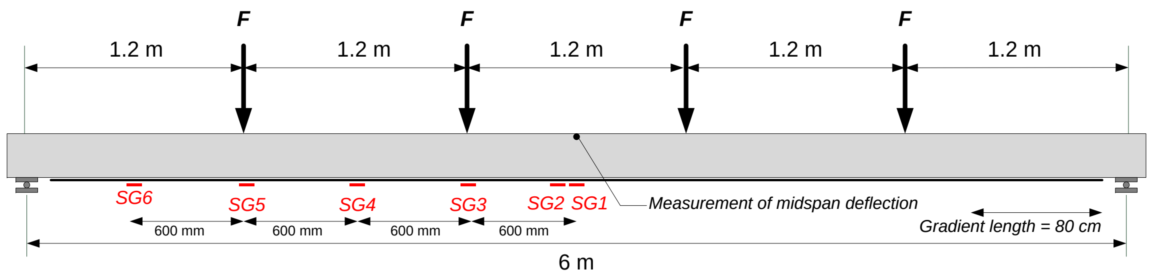


FIG. 14: Loading and measurement scheme for static beam loading (SG=strain gauge)

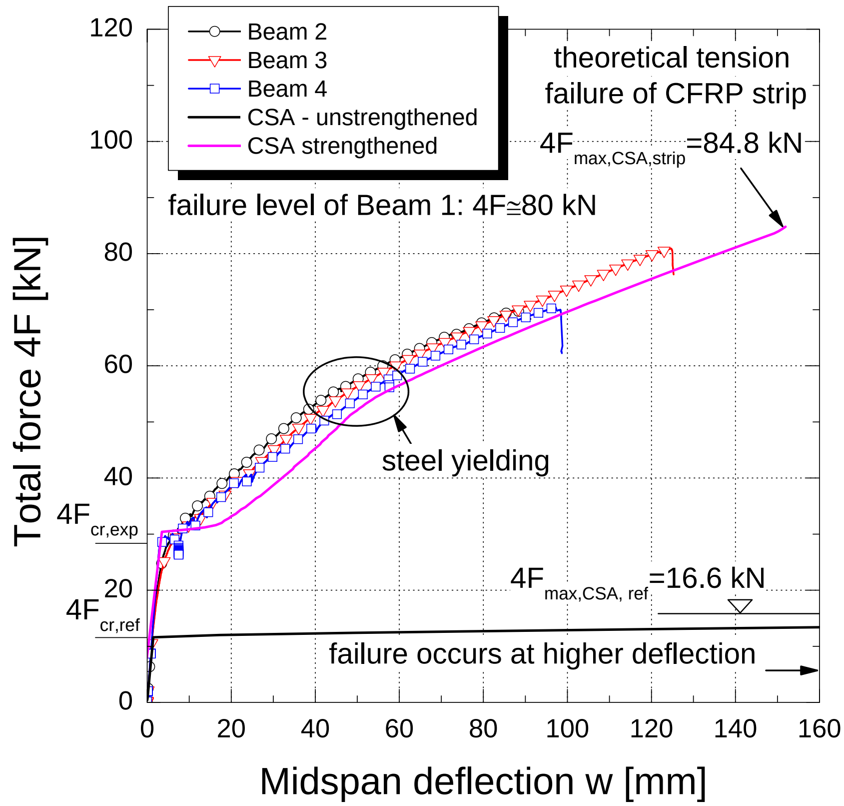


FIG. 15: Force-midspan deflection curve (no influence of dead-load measured) of the static loading tests (no force measurements available for Beam 1)

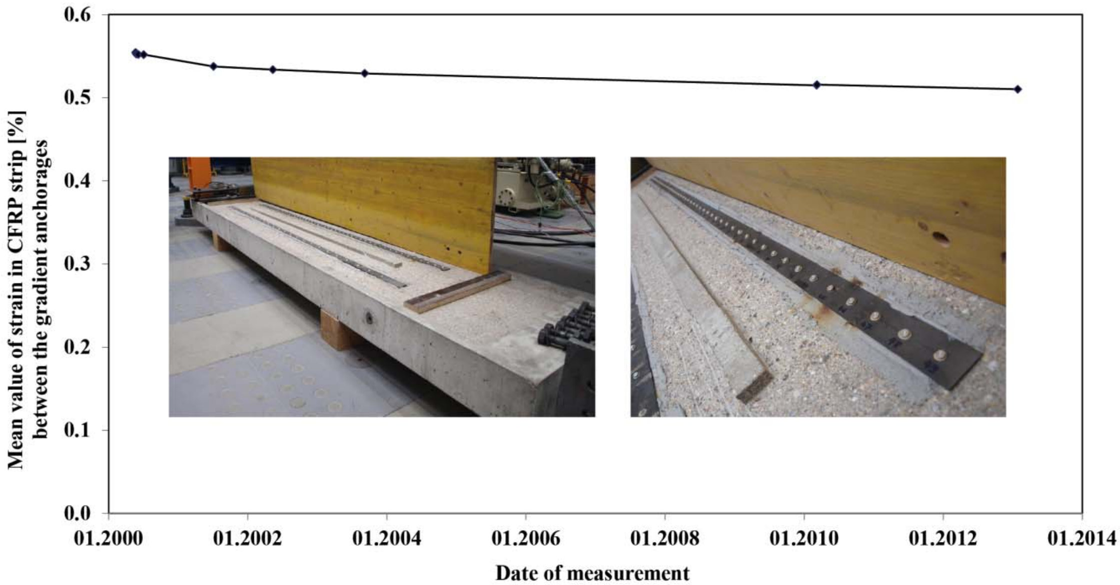


FIG. 16: Prestressed CFRP strip anchored with the gradient anchorage applied on a concrete slab and stored in the laboratory. Long-term measurement results of the CFRP strip strains by a mechanical strain gauge since the year 2000